Draft

Acceleration Scenarios for the Muon Collider

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Muon Technical Advisory Committee, July 22nd 1999

- Introduction
- Parameters
- Energy Extraction - Cavity Filling
- Power Sources

- Single Bunch Effects
- Summary + Outlook

Rf Systems being used in the MC

- Proton Driver:
  - n=2, F= (3.2-7.6 MHZ), G=(50-100kV)
  - multi-turn (msec)
- Phase Rotation:
  - n=3 or >15, F= (30-60 MHZ), G= (4-6 MV/m)
  - linac
- Cooling:
  - n=3-4, F= (60-805 MHz), G= (5-35 MV/m)
  - linac
- Acceleration:
  - n=4, F= (50-1300 MHz), G= (5-35 MV/m)
  - linac and multi-turn
- Total of 12-15 rf systems with different applications and different requirements

Parameters

- Goal: Find an acceleration scenario for the Muon Collider

Transverse Emittance:

$$\beta\gamma \cdot \varepsilon_{x,y} = \varepsilon_t^n$$

Longitudinal Emittance:

$$\beta\gamma \cdot \frac{\Delta p}{p} \cdot \sigma_z = \varepsilon_{long}^n$$

6-dimensional emittance:

$$\left[\varepsilon_t^n\right]^2 \times \left[\varepsilon_{long}^n\right] = \varepsilon_{6D}^n$$

$$\varepsilon_{6D}^n = 170 \times 10^{-12} \qquad \pi \cdot \mathrm{m}^3$$

- Number used: 170×10^{-12} (for any scenario)
- Number to start: 95×10^{-12}
  - transverse: 41×10^{-6} (π m rad)
  - longitudinal: 6×10^{-2} (π m %)
    - σ_z = 30 cm
    - $\sigma p/p$ = 11 %

High energy MC

Acceleration Limits

- Muon Decay
  - requires fast acceleration of muons

Decay Equation:

$$\frac{dN}{ds} = -\frac{1}{L_\mu \cdot \left(\gamma_0 + \gamma' s\right)} \qquad L_\mu = c \cdot \tau_\mu$$

Solution of this equation:

$$\frac{N(s)}{N_0} = \left(\frac{E_0}{E_{final}}\right)^{\frac{1}{L_\mu \cdot \gamma'}}$$

Condition for acceleration:

$$L_\mu \cdot \gamma' >> 1 \qquad L_\mu \cdot \frac{e \cdot U'_{rf}}{mc^2} >> 0.16\frac{MeV}{m}$$

Condition for acceleration in a synchrotron:

$$\frac{N_{turns}}{B[T]} << 300$$

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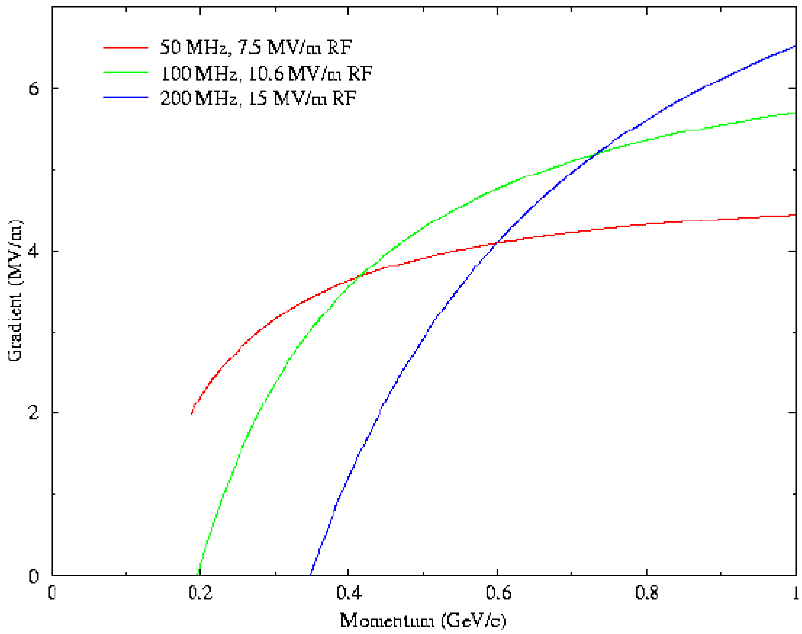
Capture and Acceleration

- After cooling:

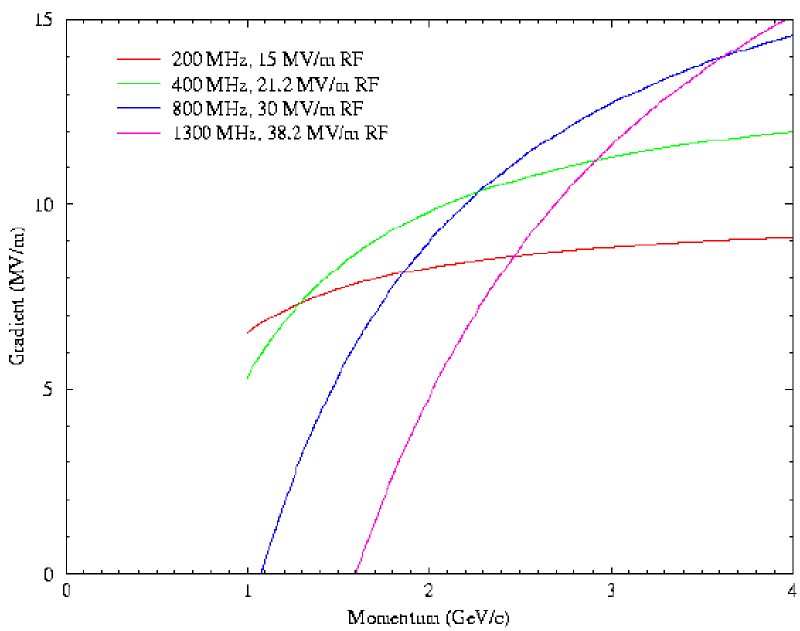


- Gradient (F)

$$G \equiv 30 \, {}^{MV}\!/_{m} \cdot \sqrt{F / 800 MHz}$$

- Emittance:
  – fix ε

$$\frac{\Delta E_{\max}}{\varphi_{\max}} \equiv \left[\frac{e \cdot G \cdot \sin(\phi_s) \cdot \gamma^3 \cdot m \cdot v_s^3}{\omega} \right]^{0.5}$$



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The Acceleration in the first Linac

How to decide what is realistic?

- Comparison to other large scale accelerating systems:
  - normal conducting systems
    - SLAC Linac: 3 GHz, 17 MV/m, 70 MW Klystrons, 280 Klystrons
    - DESY: 500 MHz, 2 MV/m, 800 kW cw, 16 Klystrons
  - super conducting systems
    - CERN: 350 MHz, 6 MV/m, 1.4 MW cw, 40 Klystrons
    - CEBAF: 1.3 GHz, ~10 MV/m, -----
    - (TESLA: 1.3 GHz, 25 MV/m, 10 MW klystrons)

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Acceleration in the Muon Collider

- Compare to LC

$$L = \frac{N^2 \cdot f_c}{4\pi \cdot \sigma_x^* \sigma_y^*} \propto \frac{P_{beam}}{E_{cms}} \times \frac{N_e}{4\pi \sigma_x^* \sigma_y^*} \times H_D$$

- Muon Collider:

Gain by: $N_e \rightarrow N_e \text{ x } f_{rev} N$

loose by: σ's

cms Energy	GeV	3000	400	100	
Pion energy	GeV	16	16	16	
Pions/bunch	10^{13}	2.5	2.5	5	
bunches/pulse		4	4	2	
rep rate	Hz	15	15	15	
beam power	MW	4	4	4	
μ / bunch	10^{12}	2	2	4	
μ beam power	MW	28	4	1	
collider circ.	m	6000	1000	300	
~depth	m	500	50	5	
rms dp/p	%	.16	.14	.12	.01
6D emittance $(\pi \text{ m rad})^3$	10^{-12}	170	170	170	
transv. Emitt. (π m rad)	10^{-6}	50	50	85	195
β*	cm	0.3	2.3	4	9
σ_r at spot	μm	3.2	24	82	187
Luminosity 10^{34}	$cm^{-2}sec^{-1}$	5	0.1	0.012	0.002

Efficient Energy Extraction

- Most efficient way:
  - run matched and cw (losses during filling of the cavity are negligible

    $\eta_{beam} \sim \eta_{klystron}$ x $\eta_{modulator}$ x $P_{beam}/P_{cavity\ walls}$
- Efficient: -> see LC
  - beam pulse (RF on +beam) is long or at least equivalent to filling time
  - keep ΔE/E per bunch under control limit Energy extraction per turn
  - ==> automatically to multi bunch scheme
- Difficult to achieve Efficiency
  - single Bunch

$$P_{beam} = \eta_{ac\to DC} \cdot \eta_{DC\to RF} \cdot \eta_{RF\to beam}$$

$$\eta_{RF\to beam} = \frac{(N \cdot e)_{pulse} \cdot U_{acc}}{P_{klystron}} * \frac{1}{3 \cdot \mathrm{T}_{\mathrm{fill}}}; \propto F^{1.5}(\mathrm{T}_{\mathrm{fill}}) \times F^{0.5}(U_{acc})$$

but limited by ΔE/E allowed in Bunch

Efficient Acceleration

- Muon Collider requires more efficient acceleration as LC or smaller emittances compared to present values
- Energy storage and Extraction

$$k = \frac{\left(\int \left| E_z(z) \cdot e^{ikz} \right| dz\right)^2}{4 \cdot W_{st}} \quad \text{(geometric const. per unit lenght}$$

$$k \propto f^2 \quad \text{(per m, for scaled cavity)}$$

$$r_{sh} = \frac{2 \cdot Q}{\omega} \cdot k \quad \text{(per m)}$$

$$r_{sh} \propto \sqrt{f} \quad \text{(for scaled cavity)}$$

$$T_{fill} = \frac{2 \cdot Q}{\omega} \propto f^{-1.5} \quad \text{(filling time)}$$

- Example: High Gradient 400 MHz Cavity, 4 MV/m

$$k = 18 \frac{V}{pC \cdot m} \cdot \left[\frac{f}{3GHz} \right]^{-2} \Rightarrow W_{st} \approx 12.5 \text{ Joule}$$

$$\mathrm{U_{acc}} = 4\,\mathrm{MV} \quad \Rightarrow \quad \mathrm{W_{ext}} / turn = q \cdot U \approx 1.6 \text{ Joule at } 2.5\text{x}10^{12}$$

$$\Rightarrow \frac{\Delta U}{U} \approx 0.5 \cdot \frac{\Delta W}{W} \Rightarrow \text{energy spread} \sim 6.5\%$$

Scaling of RF Requirements

	Comparison of RF Parameters as a Function of Frequency							
	at a Fixed Gradient of 5 and 25 MV/m and 15 Hz Rep Rate							
Gradient:	**5**	**MV/m**			**Frep:**	**15**	**Hz**	
Frequency	**Q Value**	**T_f**	**duty cycle**	**Rsh**	**Wst**	**Peak P**	**aver. P_rf**	**Aperture**
[MHz]		**[microsec]**	**10^-3**	**MOhm/m**	**Joule/m**	**MW/m**	**kW/m**	**cm**
			=3*T_f*frep				x 3*T_f	
F	F^-0.5	F^-1.5	F^-1.5	F^0.5	F^-2	F^-0.5	F^-2	F^-1
3000.00	14000	0.74	0.033	60.000	0.313	0.417	0.014	3.000
1300.00	21268	2.61	0.117	39.497	1.664	0.633	0.074	6.923
805.00	27027	5.35	0.241	31.081	4.340	0.804	0.194	11.180
500.00	34293	10.92	0.491	24.495	11.250	1.021	0.502	18.000
400.00	**38341**	**15.26**	**0.687**	**21.909**	**17.578**	**1.141**	**0.784**	**22.500**
100.00	76681	122.10	5.495	10.954	281.250	2.282	12.540	90.000
50.00	108444	345.36	15.541	7.746	1125.000	3.227	50.159	180.000
Gradient:	**25**	**MV/m**			**Frep:**	**15**	**Hz**	
3000.00	14000	0.74	0.033	65.000	7.813	9.615	0.322	3.000
1300.00	21268	2.61	0.117	42.788	41.605	14.607	1.712	6.923
805.00	27027	5.35	0.241	33.671	108.503	18.562	4.466	11.180
350.00	40988	18.65	0.839	22.202	573.980	28.151	23.623	25.714
100.00	76681	122.10	5.495	11.867	7031.250	52.666	289.380	90.000
						P_rf/ MW	P_ave/ MW	
40 m rf in the decay Channel: (50 MHz, 5 MV/m, ac_eff=35%)						129.10	5.73	
300 m rf in cooling: (100 MHz, 7.5 MV/m, ac_eff=35 %)						1540.47	24.18	
200 m rf in cooling: (350 MHz, 15 MV/m, ac_eff=35 %)						2053.96	4.03	> CERN LE
200 m rf in cooling: (805 MHz, 25 MV/m, ac_eff=35 %)						3000.00	2.55	
					TOTAL:		36.50	
TOO OPTIMISTIC ALREADY								
assuming that P_rf -> P_beam small (allmost nor P_rf needed for acceleration) -> not true for large f								

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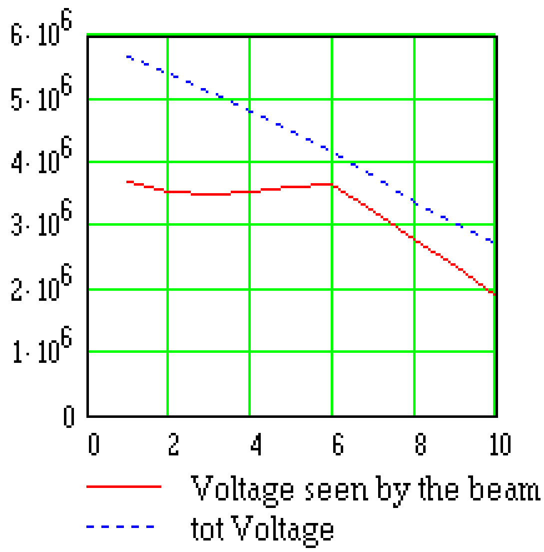
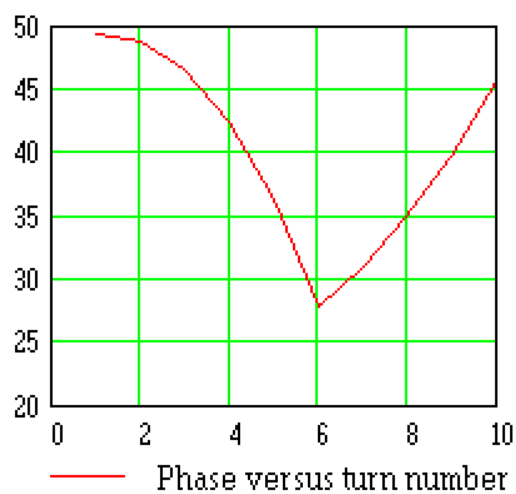
Multi-turn Acceleration

- Multi-turn acceleration in high Q device:
  - without turn by turn phase control: (FFAG):

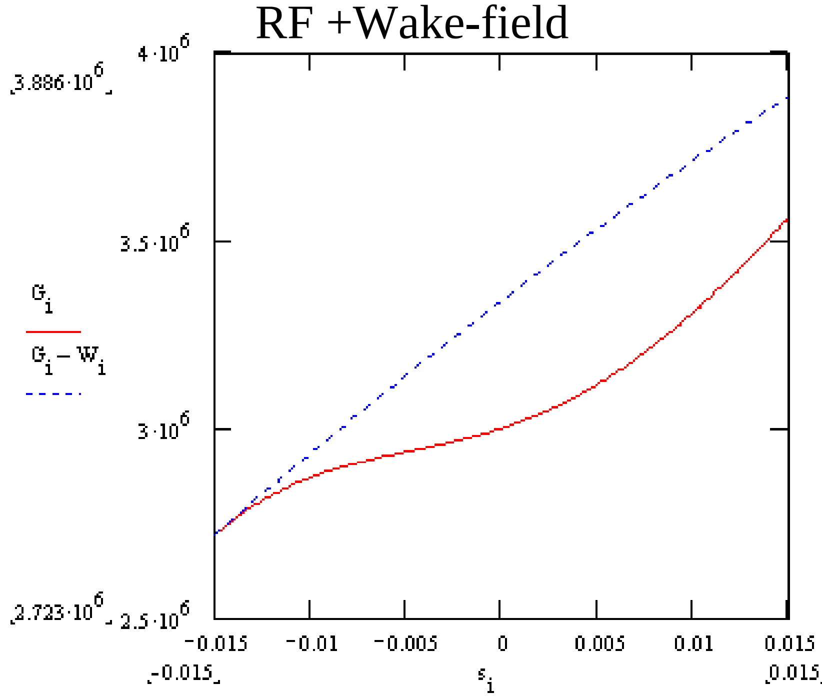




  - barely enough energy stored for 6 turns

FFAG type Acclerator		
Circumference	600	m
RF structure	300	m
Acc. Gradient	3.8	MV
Cavity Gradient	6	MV
start Phase	-48	°
Wake field ???		
Ener. Spread # 1	7	%
Power		
Power to Cav.	1.3	MW
Power to Beam	0.7	MW

RF +Wake-field



Available Power Sources

- Klystrons

- Tetrodes

Klystron Scaling in F, P, η

- Frequency:
  - in principle klystron can be scaled geometrically:

$$I = P \cdot V^{3/2}, \qquad P = \frac{4}{9}\varepsilon_0 (2 \cdot \frac{e}{m})^{0.5} \frac{A}{d^2}$$

  - if Voltage is kept const: ->Beam Power is constant
  - if current density on is kept constant -> Voltage can be increased and:
- Peak Power:
  - Ppeak ~ $1/f^2$
- Efficiency:
  - most Klystrons are build with P =$2x10^{-6}$ A/$V^{3/2}$
  - higher efficiency means: lower perveance
  - lower perveance means: higher voltage per Ampere
  - -> less beam current for the same voltage and less total power

Limits for Peak Power and Frequency

- How to determine the physical size of a klystron

Two cases:

ideal situation with no space charge:

$$z_{opt} = 1.84 \cdot \frac{u_o}{2\pi \cdot f} \cdot \frac{2}{\alpha \cdot \beta}$$

u_o := velocity of electrons = β*c = $(1-1/\gamma^2)^{0.5}$ *c

α := modulation gap voltage/beam voltage

β:= transit time

with space charge:

$$\lambda_p = \frac{2\pi \cdot u_o}{\sqrt{\frac{e}{m} \cdot \frac{n}{\varepsilon}}}$$

n := electron density

Example for Klystrons scaled with Frequency and Peak Power

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Example for 1)

f = 1 GHz, U_{gun} = 450kV , uP=1.0 , 130 MW Beam power ->
75 MW rf power,

z_{opt} := 2.8 meter only for the rf

+ gun + collector ---> easily a 5 meter long klystron with a standard approach.

Step one is the study to show a way out !!!!!!!

1. give up on efficiency and increase μP
2. go to MB devices -> happened and is going on with CPI
3. develop new rf sources

1. we would have to pay for all the development and take the risk at the same time ----> time

What about lower frequencies:

- scaling shows : z_{opt} ~ 1/f klystron becomes longer
- infrastructure in industry can not mechanically accommodate this easily
- test stands are not available
- becoming massive devices

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What to Do Now?

- Concentrate for now on the well understood territory: Two Steps:
  - do Study with CPI on high efficiency multi-beamklystron -> done by end of this FY
  - start construction with LITTON on extended version of existing 805 MHz Klystron -> go to 40 MW x 3.5

Parameter being asked for originally		
Peak Output Power	MW	80 or more
Pulse length	μsec	16 or more
Repetition rate	Hz	15 or more
VSWR		1.5, during the transient
Bandwidth	MHz	small, to be discussed
gain	dB	56 or a little less
horizontal mounting ??		

Discussions so far with LITTON and CPI

Development plan:

- Get an offer for a preliminary Study of a 805 MHZ klystron with the goal to describe the Design to be used and the approximate cost. This should be finished before end of FY 99
- Finance the development of this klystron by the Muon Collider collaboration in FY00 and 01. Development will take approximately 2 years of sign up.
- Develop the infrastructure to operate this klystron in the lab

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Recirculating Linacs

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A Long Linac

Beam Driven Instabilities

- What are the Problems:
  - Instabilities in the collider: -> dominant in the HIGGS factory ($\Delta E/E$=0.001 %)
  - Instabilities in the accelerators: ->dominant in the high energy accelerators (F >800 MHz and higher)

- How we get the solution:
  - Tools are there for the collider (-> B. NG at all)

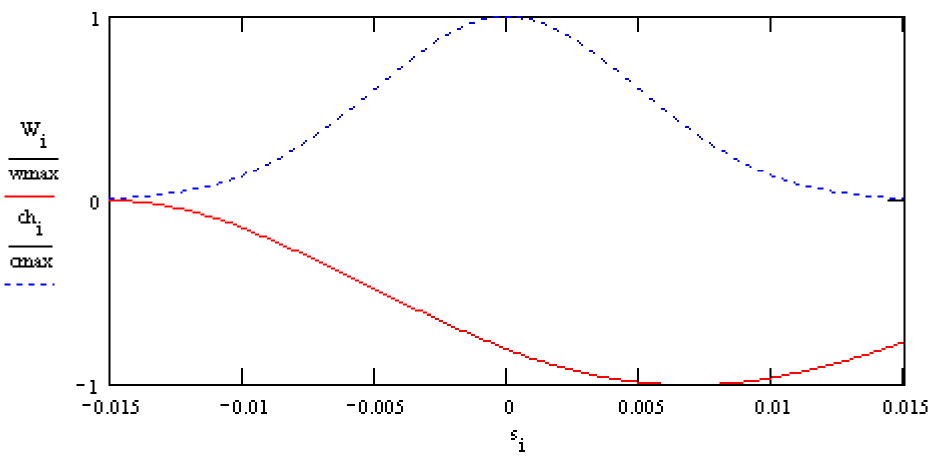
  - Tracking programs for acceleration, transverse motion and Wake Fields

Longitudinal Wake-Fields

- Linac Type Acceleration: no synchrotron oscillations

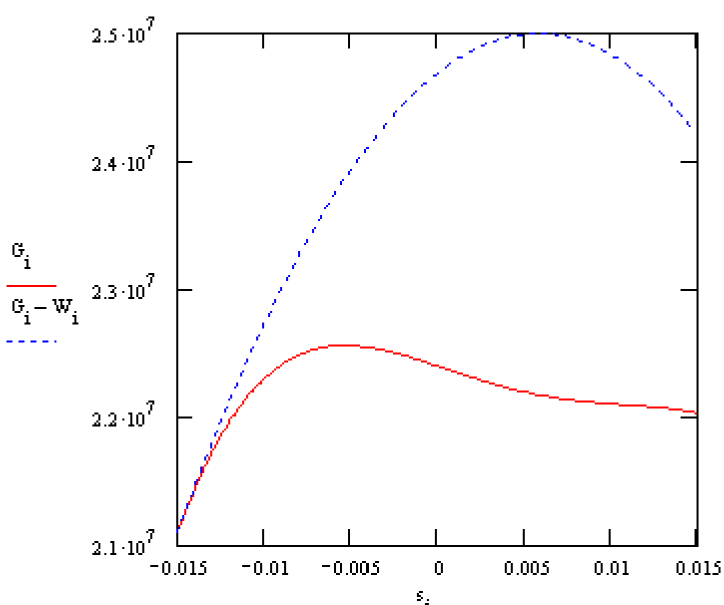
wmax := max(-W) $wmax \cdot \frac{m}{V} = 2.837 \cdot 10^{6}$
cmax := max(ch)

Wake-field



RF +Wake-field

$\varepsilon = 6.526 \cdot 10^{-5}$ m



Frequency	500	MHz
Gradient	5	MV
Energy spread	1.3	%
Phase	12	°
Accel. loss	7	%
bunch σ	5	mm

reduce charge per bunch
more bunches

Tolerances

- Transverse Wakefield
  - scale like the the frequency cubed
  - in a high energy linac the driving force for emittance degradation

Two particle Model

$$x_1'' + k^2 x_1 = 0$$

$$x_2'' + (k+\Delta k)^2 x_2 = C \cdot x_1 \qquad , C = \frac{e \cdot N \cdot W_\perp' \cdot \sigma_s}{2 \cdot E}$$

$$\frac{x_2 - x_1}{\bar{x}} = \frac{C \cdot s}{2ik} \cdot e^{iks}$$

$$\Rightarrow \frac{\Delta\varepsilon}{\varepsilon} \propto \frac{e \cdot N^2 \cdot F^6 \cdot \sigma_s}{G^2 \cdot L^2 \cdot k \cdot \varepsilon}$$

Emittance growth

$$\Rightarrow \frac{\sigma}{E} = \frac{e \cdot N \cdot W_\perp' \cdot \sigma_s}{2 \cdot k^2 \cdot E}$$

Required energy spread

Tolerances compared to LC

- Take example TESLA
  - 20 km rf structure
- MC -> 5 km per turn

TESLA		
Bunchlength σ	0.7	mm
W'*σ	26	V/pC/m^2
$k_\beta=2\pi/\beta$	0.06	1/m
N	2	10^{10}
Length	14	Km
$\gamma\varepsilon$ $x10^{-6}$	0.03	m
Muon Collider 1.3 GHz		
Bunchlength σ	5	mm
W'*σ	70	V/pC/m^2
Acc. Gradient	25	MV/m
$k_\beta=2\pi/\beta$	0.12	1/m
N	4	10^{12}
Length	5	Km
$\gamma\varepsilon$ $x10^{-6}$	50	m

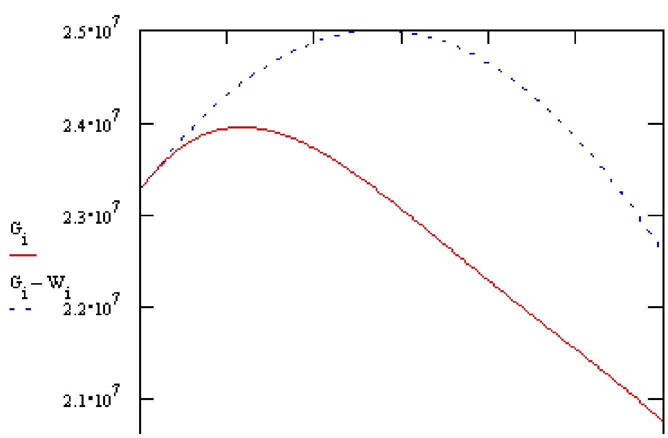
Alignment tolerances are ~ 1/2.
For same length: 2x tighter

- HOM losses (relevant for sc rf):
  - W_{long} ~sqrt(σ)
  - $W_{loss} = Q^2*k$ => x 3700

Tolerances and BNS

- Frequency F^3+geom.: x 12 x1.6=20
- Bunch length sqrt(σ): x 2.2
- Energy 1/E: x 5
- Bunch Charge N: x 125
- β-wave number k^2: x 1 (very opt.)
- Total x 2.75

BNS phase=0



SLC. 3GHz		
Bunchlength σ	1	mm
W'	1500	V/pC/m^2
Acc. Gradient	17	MV/m
$k_\beta=2\pi/\beta$	0.06	1/m
N	2	10^{10}
Energy	25	GeV
σ/E	1.5	%
Muon Collider 1.3 GHz sc		
Bunchlength σ	5	mm
W'	70	V/pC/m^2
Acc. Gradient	25	MV/m
$k_\beta=2\pi/\beta$	0.06	1/m
N	2.5	10^{12}
Energy	125	GeV
σ/E	4.1	%

c

Do this with an RFQ ?
4% of magnet Focussing
with RF field ?

Synchrotrons

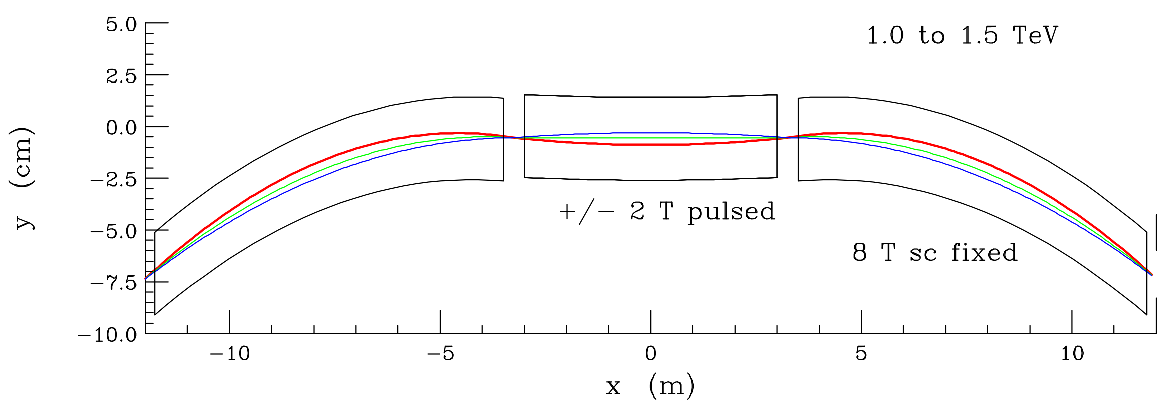
- Based on MI Dipole Magnetic Data:

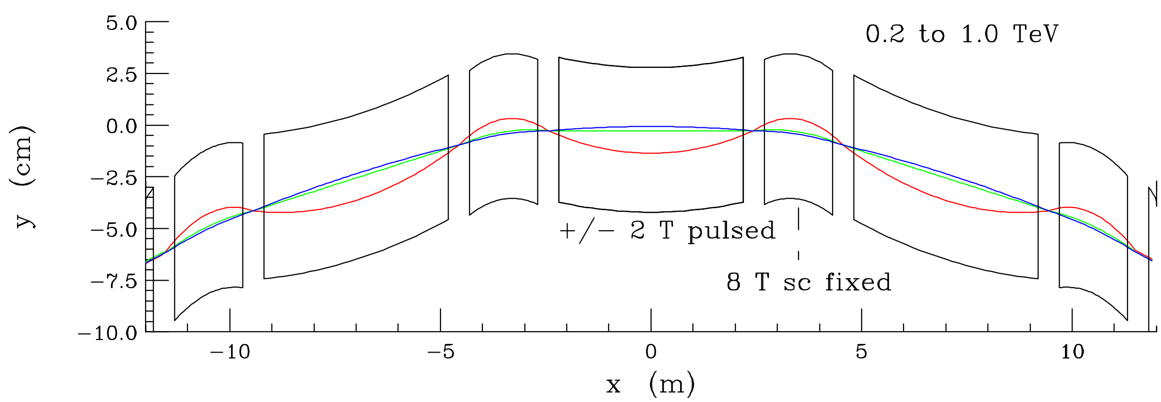
Example Synchrotron		
Energy	150 – 2000	GeV
ave. radius ρ	5	km
cycle rate	15	Hz
Dip. Inductance	0.3	mH/m
Filling fact.	0.7	
B_{max}	1.7	T
I_{max}	9	kA
Synchrotron Parameter		
Inductance	8	H
U_{ind}	400	kV
P_{ave} ->copper	140	MW
Laminat. Thick	0.5	mm
P_{ave} ->laminat.	70	MW
Vacuum Chamb.	???	
RF (for accel)	27 (19)	GeV
(13xLEP install.)		
may be at lower rep rate		

- At lower rep. Rate this is a may be …

Pulsed Rings (~ Synchrotrons)

- Pulsed Magnets ? Should disappear from Baseline or need severe R&D program
  - 360 μsec ramp time
  - 9kV at each magnet
  - very expensive iron laminations (metglas, 0.025 mm)
  - sc type cable with up to 24 kA (transposed strands)
  - fast ramping rf in the ring
  - completely unclear beam dynamics





Necessary Steps

- Transverse and Longitudinal Stability are both an issue
  - Need a tracking program to simulate these effects
  - concrete piece of work…..
    - issue for collaboration: Post Docs or people interested in BD should start working on it
    - try to get Fermi-people involved in this
  - Investigate what actually is necessary to achieve small energy spread, as eg in the HIGGS Factory
- Reconsider more bunches
- Reconsider more Pions per second
- Reconsider smaller emittance
- Certainly push for more higher Frequency systems